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BURNING OF CONDENSED ALUMINIZED SYSTEMS
UNDER OVERLOAD

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь: e elsewhere.
When written as ё in Russian, transliterate as yё or ё.
The use of diacritical marks is preferred, but such marks
may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

———

Russian	English
rot	curl
lg	log

BURNING OF CONDENSED ALUMINIZED
SYSTEMS UNDER OVERLOAD

S. K. Ordzhonikidzye, A. D. Margolin,
P. F. Pokhil, and A. S. Uralov

In a number of cases inertial forces applied to a burning
substance significantly increase the burning rate [1-13]. This
is due to the fact that the inertial forces force the hot condensed
particles which have formed in the combustion process to the
burning surface. In the present study the burning of aluminized
systems is studied experimentally and theoretically.

Method of Experiment

Measured were the combustion rate, mass, and composition of
slags forming in a condensed system consisting of 70% ammonium
perchlorate, 15% rubber, and 15% aluminum powder with a particle
dimension size of about 10 µm. The studied specimens had a
cross section area of 0.4 cm^2 and a length of from 0.5 to 1.5 cm.
The lateral surface of the specimens was covered with an epoxy
resin, after which they were glued into a quartz tube, 4 cm long,
with epoxy resin. For the purpose of creating the overloads the
specimen was attached radially to a disc (radius 4.5 cm), which
together with the electrical motor which rotated it was placed
in a vessel with a volume of 2 l. Prior to the experiment the

vessel was filled with nitrogen under a pressure of 30, 60, or 100 atm. Then, when the disc reached a constant rate of rotation, an electrical igniter was used to ignite the specimen. The combustion rate was determined from an oscillogram showing the pressure increase in the vessel. During the experiment pressure increased by no more than 5 atm. The combustion rate was referred to the average pressure during the combustion process and to mean acceleration, i.e., to the acceleration in the middle of the specimen.

Results of Experiments

In the absence of overloads the studied composition burns at a rate of 1.1 cm/s at 30 atm, 1.3 cm/s at 60 atm, and 1.5 cm/s at 100 atm. As acceleration is increased up to 200 g the combustion rate of specimens 1.5 cm long increases 1.5 times, and the increase in the combustion rate is proportional to the square root of acceleration (figure 1). After the specimen had been burned up in the massive copper crucible in which it was placed there remained a lump of finely porous grey slag with a specific weight of 2.8 g/cm^3. The slag consisted primarily of aluminum oxide. Volumetric analysis revealed no metallic aluminum in the slag. In [7, 10] it was also shown that the slag which remains after burning under overloads consist primarily of aluminum oxide. In the case of small overloads the slag has the form of agglomerates of several small spheres of about 100 μm in diameter, at greater accelerations the residue consists of 2 or 3 lumps, under maximal accelerations - of a single lump. If an opening is made in the crucible, then during the experiment the slag flows out of it. Consequently, while it is burning the aluminum oxide is in a molten state. The mass of remaining slag increases with acceleration (figure 2) and is proportional to the mass of the burned specimen (figure 3). These results were obtained from specimens of different lengths with cross section areas of from 0.03 to 0.5 cm^2. The effect of increasing the combustion rate under

overloads diminished as the length of the specimen increased (figure 4). Negative accelerations did not effect the combustion rate.
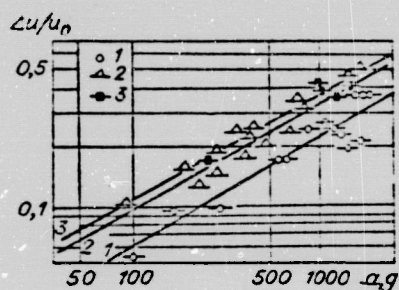

Figure 1. Relative increase in combustion rate $\Delta u/u_0$ as a function of acceleration a, expressed in units of g (g=980 cm/s^2) at pressures of 33 (1), 64 (2), 104 atm (3) for specimens 1.5 cm long.
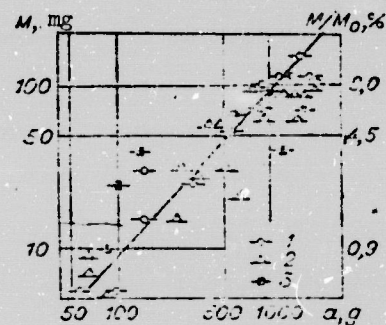

Figure 2. Scale mass M as a function of relative scale mass M/M_0 (M_0 is the original mass of the specimen) as a function of acceleration a under pressures of 33 (1), 64 (2), and 104 atm (3) for specimens 1.5 cm long.
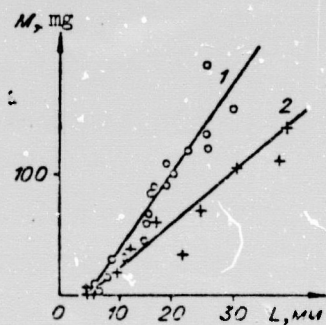

Figure 3. Scale mass M as a function of original length of specimen L under acceleration of 1500 g (1) and 400 g (2) and a pressure of 60 atm.
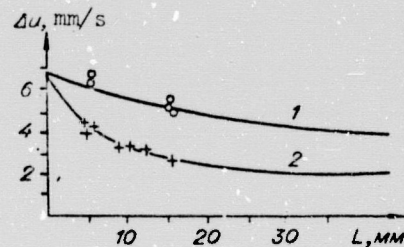

Figure 4. Increase in combustion rate Δu as a function of specimen length L under accelerations of 1500 g (1) and 400 g (2) and a pressure of 60 atm. Curves are theoretical.

Combustion Model

Based on the experimental data on the increase in the combustion rate and fill-up of the mass of slag consisting of aluminum oxide, we proposed a following combustion model for aluminized systems under overloads.

The aluminum particles which are held by inertial forces near the combustion surface form drops of slag as they burn, and these merge, forming large drops. On the surface of the molten drops of slag from the burning specimen new aluminum particles constantly emerge. These are easily ignited from the high-temperature surface of the slag drops, and burn on this surface, increasing the mass of the slag drop. The holding of the hot aluminum drops near the combustion surface facilitates more complete burning of the aluminum and conversion into aluminum oxide.

The presence near the surface of the condensed system of high-temperature slag drops held by inertial forces increases the local combustion rate under the drop, since heat transfer from the high-temperature surface of the drop to the combustion surface occurs through a small gap between the drop and the combustion surface. Here depressions are formed under the drop on the combustion surface. If the number of slag drops above the surface is sufficiently great, then the joining of neighboring depressions occurs rapidly and the combustion rate on the surface becomes equal to the local combustion rate. As the slag drops grows during combustion the gap between the drop and the combustion surface increases (see formula (2)), which causes a reduction in the heat flux toward the combustion surface and, consequently, a weakening in the effect of the increase in combustion rate. The size of the particle cannot increase infinitely, since under the effect of the circumfluent flow of combustion gases the surface of a rather large drop becomes unstable and the drop breaks up. When

the slag drops have reached their maximal dimension the slag mass under the combustion surface ceases to build up, since the increased mass of the drops is, due to the influx of new particles, compensated by the removal of small drops during break-up. This would correspond to a stationary combustion mode.

In [7] an open calculation is proposed, in which the size of the drop would remain unknown. Let us move on to construct a closed theory.

We will assume that the molten slag drop, consisting of aluminum oxide, has an aluminum oxide melting point of $T_{\text{к}} = 3500°K$ and the nearing of the drop to the combustion surface changes the temperature gradient ϕ in the combustion zone

$$\varphi = \frac{T_\kappa - T_\pi}{l},$$

where l is the distance between the surface of the drop and the combustion surface; $T_{\text{к}}$ - temperature of the drop; T_π - temperature of burning surface.

Let us assume the following relationship between combustion rate u and temperature gradient ϕ:

$$u = \sqrt{u_0^2 + k_1^2 \varphi^2} = \sqrt{u_0^2 + k^2/l^2}, \tag{1}$$

where $k = \frac{\lambda_\tau (T_\kappa - T_\pi)}{\rho_\tau\, c_\tau (T_\pi - T_0)};$ u_0 is the normal combustion rate; λ_Γ - the coefficient of heat conductivity of the combustion gases; ρ_τ - density of k-phase; c_τ - heat capacity of k-phase.

The gas dynamics calculation of [7] for a spherical drop of the radius r, suspended in the depression on the specimen

of the surface so that gap l below it has parallel walls, can
be used to determine the width of the gap from the condition of
balance of inertial forces and gas pressure under the globule:

$$l = 0.7 u \rho_{\text{т}} (1-w) \sqrt{\frac{r}{\rho_{\text{к}} \rho a}} , \qquad (2)$$

where a is centrifugal acceleration, w - concentration of Al,
$\rho_{\text{к}}$ - drop density, ρ - density of gases.

If we substitute (2) in equation (1) and carry out certain
transformations, then we get the following dependence for the
relative combustion rate $Z = u/u_0$:

$$Z^2 (Z^2 - 1) = \frac{2k^2 \rho_{\text{к}} \rho_a}{(1-w)^2 \rho_{\text{т}}^2 u^4 r} . \qquad (3)$$

when $Z \gg 1$

$$Z \sim \frac{\rho^{0.25} a^{0.25}}{(1-w)^{0.5} u_0 r^{0.25}} , \qquad (4)$$

which is in qualitative agreement with the equation obtained in
[7] under condition u>1, 2 u_0,

$$Z = 2\left[\frac{r}{b} \left(\frac{\rho_{\text{к}} \rho a}{r} \right)^{1/4} \frac{\eta^{1/2} k}{\rho_{\text{т}} u_0 (1-w)} - 0.2 \right] + 1, \qquad (5)$$

which, when $Z \gg 1$, has the form of

$$Z \sim \frac{\rho^{0.25} a^{0.25}}{(1-w) u_0 r^{0.25}} . \qquad (6)$$

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For a slight increase in combustion rate, i.e., when $Z \approx 1$, we get from equation (3)

$$Z - 1 \sim \frac{\rho a}{u_0^4 r} .$$

Thus, a dependence has been obtained for the relative combustion rate as a function of the percent concentration of aluminum in the specimen, gas density, acceleration, normal combustion rate in the absence of overloads, and the radius of the slag drop. From equation (3) it follows that the lower the normal rate of combustion, the more intense will be the effect of the increase in combustion rate under overloads; when the effect is rather great (4) combustion rate u does not depend on the normal rate. In physical terms this means that under low normal combustion rate u_0 the participation of combustion itself is low as compared to the influx from the high-temperature slag drops. This has been confirmed by experimental data (figure 5).
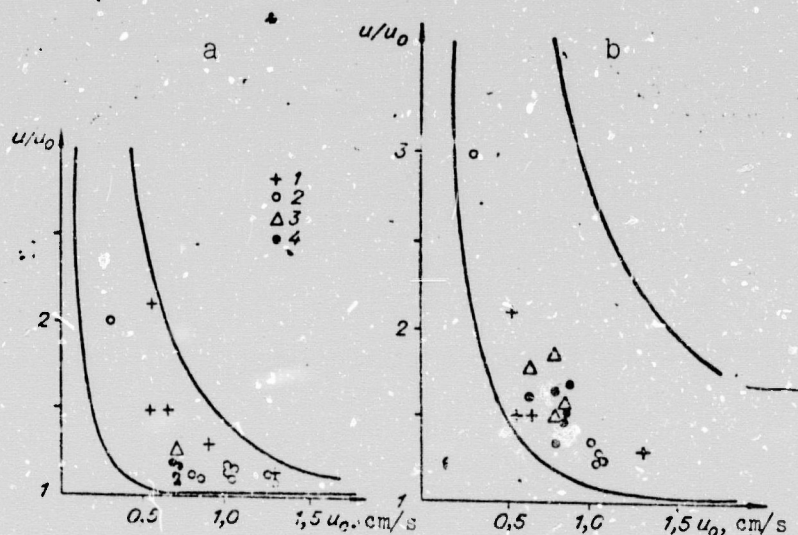

Figure 5. Relative combustion rate u/u_0 as a function of the initial combustion rate u_0 at pressure of 70 atm accelerations of 100 g (a) and 1000 g (b). 1 - data of present work in [1], L=15 mm; 2 - L=57 mm [5]; 3 - L=25.5 mm [10]; 4 - L=58.5 mm [10].

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Experimental combustion modes. The maximal increase in combustion rate corresponds to drops of minimal radius r_{min}, which is determined [14] from the condition of equality between drop weight and hydrodynamic resistance forces (drops of smaller dimensions would be carried away by the flow)

$$r_{min} = \sqrt{h \frac{v_r \eta}{\rho_{\kappa} a}}, \qquad (7)$$

where v_r is the velocity of the flow of gases around the drop at a distance from the combustion surface; η - coefficient of dynamic viscosity of combustion gases; h - coefficient, equal to 9/2 at Re<<1 (Stokes equation) and 9 when Re>>1 (Levich equation).

From the equation of material balance between the mass of specimen used and gas influx per unit time over one unit surface (assuming that the aluminum is not converted into gas during combustion) we get

$$u \rho_T (1 - w) = v_r \rho. \qquad (8)$$

The value v_r is substituted in equation (7), and then

$$r_{min} = \sqrt{h \frac{u \rho_T (1 - w) \eta}{\rho_{\kappa} \rho a}}. \qquad (9)$$

For the maximal increase in velocity we get, by using (3) and (9) and making appropriate transformations,

$$Z_{max}^{2,5} (Z_{max}^2 - 1) = \frac{k^3 \rho_{\kappa}^{1,5} \rho^{1,5} a^{1,5}}{\rho_T^{2,5} \eta^{0,5} (1 - w)^{2,5} u_0^{4,5}}. \qquad (10)$$

For $Z_{max} >> 1$

$$Z_{max} \sim \frac{\rho^{0,33} a^{0,33}}{(1 - w)^{0,55} u_0}$$

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and $Z_{max} \approx 1$

$$Z_{max} - 1 \sim \frac{\rho^{1.5} \sigma^{1.5}}{(1-w)^{2.5} u^{4.5}} .$$

The minimal rate increase is determined by the maximal possible dimension of the drop. Above this dimension the surface of the drop becomes unstable and it breaks down into droplets: their size is less than r_{min} and they are carried away by the flow. The rate of dispersion of this unstable drop is very high. The size of the small droplets which are separated from the surface of the unstable drops are determined, in order of magnitude, by the length of the unstable wave [14] according to the equation

$$r_{min} \approx \frac{\sigma_{\kappa}}{\rho v_3^2} , \tag{11}$$

where σ is the surface tension of the drop; v_3 the outlet velocity of the gas flowing from the gap under the drop held on the combustion surface.

The outlet velocity of the gas from the gap is determined by the balance between the gas coming from the surface of the specimen and the gas flowing away over the surface of the gap outlet (we assume that the gap ends in the equatorial plane of the drop and that l is small compared to r of the drop), i.e.,

$$u \rho_\tau (1-w) 2\pi r_{max}^2 = v_3 \rho 2\pi r_{max} l_{max} ,$$

from which we get

$$v_3 = \frac{u \rho_\tau (1-w) r_{max}}{\rho l_{max}} . \tag{12}$$

If we use equation (2) for l and equation (12), then we can balance the equation for r_{min} from equation (11) with r_{min} from

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equation (9), according to the condition of the existence of a drop of maximal radius. The droplets are separated (11) from the surface of the large, unstable drop by a gas flow moving at a rate of v_3 at the gap outlet and are carried away (9) by a flow of gas moving at a lower velocity of v_r outside of the gap. After making the transformations, we determine critical maximal dimension of the drop

$$r_{max} = 0.25\sigma_\kappa \sqrt{\frac{\rho}{u\rho_r(1-\omega)\eta_\kappa a}}. \tag{13}$$

If we substitute this expression in equation (3), we get

$$Z_{min}^{1.5}(Z_{min}^2 - 1) = \frac{8k^2\sigma_\kappa^{1.5}\tau^{0.5}\rho^{0.5}a^{1.5}}{\sigma_\kappa\rho_r^{1.5}(1-\omega)^{1.5}u_0^{3.5}} \tag{14}$$

Where $Z_{min} \gg 1$

$$Z_{min} \sim \frac{\rho^{0.14}a^{0.42}}{(1-\omega)^{0.42}u_0}$$

and when $z_{min} \approx 1$

$$Z_{min}' - 1 \sim \frac{\rho^{0.5}a^{1.5}}{(1-\omega)^{1.5}u_0^{3.5}}.$$

Thus, the drops of slag can have a dimension of $r_{min} < r < r_{max}$, to which we have the corresponding relative rate increase of $Z_{max} > Z > Z_{min}$.

The plotting of the dependence of Z_{max} and Z_{min} as a function of u_0 in figure 5 shows that all experimental data on the dependence of Z and u_0 are included between these limiting values. However, in all cases where acceleration is so great that the

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dimension of particles on the specimen is greater than r_{min} and where agglomeration and merging of molten particles take place, the original rate value $Z_{нач}$ will always be less than Z_{max}.

Transition mode in combustion. Since the slag drops in the combustion process increase in size, then there should exist a transition regime between the original rate increase $Z_{нач}$ and the limiting Z_{min} if the length of the specimen permits the limit to be reached. For this we must show how the size of the drop changes during the combustion process. We can represent the growth of the drop as being proportional to the combustion surface of the specimen under the drop. With a simple calculation we can show, in fact, that the size of the drop is comparable to the size of the depression.

Let us assume that

$$\frac{dm}{dt} = wvu\rho_\tau s, \qquad (15)$$

where m is the mass of the drop, s - the combustion surface under the drop (hemisphere); v - the fraction of burned Al which enters the drop of slag. If we make the following replacements in equation (15)

$$m = \rho_к V = {}^4/_3 \pi r^3 \rho_к,$$
$$s = 2\pi(r+l)^2$$
$$udt = dL.$$

where L is the length of the burned part of the specimen, and if we use equations (2) and (3), we get, after a series of transformations, the following dependence for drop size r and the relative combustion rate Z as a function of the length of the specimen L:

$$r = 0,5wv \frac{\rho_\tau}{\rho_к} L + r_0;$$

$$Z^2(Z^2 - 1) = \frac{2k^2 \rho_к \rho a}{(1-w)^2 \rho_\tau^2 u_0^4 \left(0,5wv \frac{\rho_\tau}{\rho_к} L + r_0\right)}, \qquad (16)$$

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where r_0 is the size of the slag drop when burning begins.

For Z_{min}, the length $L_{\text{пере}x}$ of the specimen section on which the transition regime occurs is determined as follows:

$$L_{\text{пере}x} = \frac{0.5z_{\kappa}}{v w_{\tau}} \sqrt{\frac{?}{\tau(1-z)\,p_{\tau}au_0} - \frac{2\gamma_0}{v w p_{\tau}}}.. \qquad (17)$$

If we assume that v=0.05, then we get good agreement between the theoretical dependence Z=f(L) (16) and our experimental data for a=400 g and a=1500 g (see figure 4) and the data of Reichenbach [10] for accelerations of 100 and 400 g, respectively, (u_0=0.965 cm/s, p=35 at). Here the initial radius of the drop at L=0 according to formula (3) for 400 and 1500 g is equal, according to the calculation, to 14 and 51 μm, respectively; this value is about 200 μm according to the data of Reichenbach for both accelerations. This is because the radius of the particles on the specimen in our experiments is 5 μm and is 28 μm in [10]. If we assume that at the initial moment the drops have a size which can be determined by the agglomeration and the merging of particles on the surface, then it is obvious from the results presented above that an increase in overloads can increase the size of the agglomerates. The use of this theory for experimental data on the initial combustion period of the specimen under different overloads and the extrapolation of these data to zero overloads is one method of determining the degree of agglomeration and fusing of aluminum particles on the surface.

Thus, combustion is broken down into two stages: a rapid decrease in the effect in the first several centimeters of the specimen, then a slow decline in the relative combustion rate Z to Z_{min}, which according to the theoretical calculation for 1500 g in our case is reached at a consumption of about 50 cm of the specimen. Here the slag drops have a maximal dimension of 1000 μm. The closer the initial dimension of the drop to the maximal, the shorter will be the length of the transition sections.

If we assume that there is a single-dispersed layer of drops above the combustion surface, a layer which also determines the increase in the combustion rate, then the mass M of this layer is determined by the product of the number of drops in above a combustion surface with area S by mass m of a single drop.

$$M = n \cdot m,$$

where

$$n = \frac{S}{\sigma} q,$$

here σ is the cross section area of the drop; q - space factor (q≈0.5).

After transformations we get the dependence between the slag mass and the length of the specimen

$$M = 4/3 q S \rho_{\kappa} \left(0,5 \varpi v \frac{c_\tau}{c_\kappa} L + r_0 \right). \qquad (18)$$

If we use equations (17) and (18), then we get the following expression for the maximal size of the slag mass, which results from the maximal size of the drops r_{max}:

$$M_{\text{пред}} = 0,33 q S \sigma_{\kappa} \sqrt{\frac{2v^2}{(1-\omega) c_\tau \tau a u_0}}. \qquad (19)$$

For S=0.4 cm^2 (in our experiments) we get $M_{\text{пред}} \approx 100$ mg (for 1500 g). According to formula (18) the slag mass must grow linearly with length, reaching the same value at the same specimen length outside of the acceleration dependence. Actually (see figure 3) although the mass grows linearly with specimen length, it grows faster at higher accelerations and has already reached higher $M_{\text{пред}}$ values at specimen lengths which are less than the calculated

limit L_{nepex}. This means that the mass calculated according to formula (18) is a minimal mass, and, in actuality, can be a polydisperse layer of drops, in which case the combustion rate is determined solely by the drops of least dimension in the lower part of the layer closest to the combustion surface. However, in the combustion process the drops merge, grow in dimension, and attain the maximal possible dimension determined by equation (13). It is obvious that this layer will also be monodisperse and that its mass will be equal to $M_{пред}$. Consequently, in the combustion process the entire mass of slag can in a certain moment be greater than the limiting. Then, as the drops shift from the polydisperse layer to the limiting monodisperse, this mass decreases $M_{пр д}$ and thereafter remains constant.

Thus, the proposed model explains observed experimental dependences and enables us to predict a number of others. It is obvious that if the pattern is to be complete we must know the initial size of the slag drops and the dependence of this size on the acceleration value. Thus it is necessary to measure the combustion rate in the combustion process from the very first moment. We also need a theory which describes the behavior of the polydisperse layer of drops during combustion, since the transition regime can be rather prolonged. However, for a combustion process in a limiting stationary mode the proposed theory enables us to determine the combustion rate, drop size, magnitude f drops carried away, and slag mass.

Conclusion

1. As overloads grow the combustion rate and mass of slag residue increases. Here compositions which burn rapidly are less sensitive to overloads.

2. As the length of the specimen increases the slag mass is increased and the average combustion rate decreased.

3. The theoretical combustion model for aluminized systems with overloads is in good agreement with the data of our experiments and the data from other authors.

4. The maximal and minimal increase in the combustion rate and duration of the transition regime as a function of overloads and characteristics of the system, along with the size of particles carried away from the combustion surface and the mass of slag in the stationary combustion regime, have been theoretically predicted.

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